Mon. Not. R. Astron. Soc. **000**, 1–?? (2011) Printed 8 March 2013 (MN LaTeX style file v2.2)

On the spectrum of the pulsed gamma-ray emission from 10MeV to 400GeV of the Crab pulsar.

N. Chkheidze[1],* G. Machabeli[1] and Z. Osmanov[2]
[1] *Centre for Theoretical Astrophysics, ITP, Ilia State University, Tbilisi, 0162, Georgia*
[2] *Free University of Tbilisi, Tbilisi, 0183, Georgia*

8 March 2013

ABSTRACT

In the present paper a self-consistent theory, interpreting the VERITAS and the MAGIC observations of the very high energy pulsed emission from the Crab pulsar is considered. The photon spectrum between 10MeV and 400GeV can be described by two power-law functions with the spectral indexes equal to 2 and 3.8. The source of the pulsed emission above 10MeV is assumed to be the synchrotron radiation, which is generated near the light cylinder during the quasi-linear stage of the cyclotron instability. The emitting particles are the primary beam electrons with the Lorentz factors up to 10^9. Such high energies by beam particles is supposed to be reached due to Landau damping of the Langmuir waves in the light cylinder region. This mechanism provides simultaneous generation of low (radio) and high energy (10MeV-400GeV) emission on the light cylinder scales, in one location of the pulsar magnetosphere.

Key words: instabilities - plasmas - pulsars: individual (PSR B0531+21) - radiation mechanisms: non-thermal

1 INTRODUCTION

The recent observations of the Crab pulsar in the very high energy (VHE) domain with the VERITAS array of atmospheric Cherenkov telescopes revealed pulsed γ-rays above 100GeV (Aliu et al. 2011), which was later confirmed by measurments of the MAGIC Cherenkov telescope (Aleksić et al. 2011, 2012). Prior to the work Aliu et al. (2011) the highest energy of the pulsed emission from the Crab pulsar was 25GeV (Aliu et al. 2008). The detection of such a high energy pulsed γ-rays cannot be explained on the basis of current pulsar emission models. It is generally assumed that the VHE emission is produced either by the Inverse Compton scattering or by the curvature radiation. By analyzing the aforementioned emission processes (Machabeli & Osmanov 2009, 2010), we have found that for Crab pulsar's magnetospheric parameters even very energetic electrons are unable to produce the photon energies of the order of 25GeV. Studying the curvature radiation, it was shown that the curvature drift instability efficiently rectifies the magnetic field lines, leading to a negligible role of the curvature emission process in the observed VHE domain (Osmanov et al. 2009). In previous work Chkheidze et al. (2011) we have explained the origin and the measured spectrum of the Crab pulsar in the high energy (HE) domain $(0.01 - 25)$GeV, relying on the pulsar emission model first developed by Machabeli & Usov (1979). According to these works, in the electron-positron plasma of a pulsar magnetosphere the low frequency cyclotron modes, on the quasi-linear evolution stage create conditions for generation of the HE synchrotron radiation.

It is well known that the distribution function of relativistic particles is one dimensional at the pulsar surface, because any transverse momenta ($p_\perp$) of relativistic electrons are lost in a very short time ($\leqslant 10^{-20}$s) via synchrotron emission in very strong magnetic fields. But plasma with an anisotropic one-dimensional distribution function is unstable which inevitably leads to the wave excitation process. The main mechanism of the wave generation in plasmas of the pulsar magnetosphere is the cyclotron instability, which develops at the light cylinder length-scales (a hypothetical zone, where the linear velocity of rigid rotation exactly equals the speed of light). During the quasi-linear stage of the instability a diffusion of particles arises as along, also across the magnetic field lines. Therefore, plasma particles acquire transverse momenta and, as a result, start to radiate in the synchrotron regime.

In Chkheidze et al. (2011), it was shown that near the light cylinder the radio waves are generated, provoking the re-creation of the pitch angles and the subsequent synchrotron radiation in the HE domain. Thus, in the framework of this model generation of low and high frequency waves is a simultaneous process and it takes place in one location of the pulsar magnetosphere. This explains the ob-

* E-mail: nino.chkheidze@iliauni.edu.ge

served coincidence of the HE emission pulses with the radio signals. The recent VERITAS and MAGIC observations have shown that the aforementioned coincidence takes places in the VHE domain (> 100GeV) as well (Aliu et al. 2008, 2011; Aleksić et al. 2011). According to Aliu et al. (2011) detection of pulsed γ-ray emission of the order of 100GeV requires that the emission should be produced far out in the magnetosphere. Thus, we suppose that the pulsed high and the very high energy radiation of the Crab pulsar is generated through the synchrotron mechanism at the light cylinder length-scales, switched on due to the quasi-linear diffusion. The resonant particles are the primary beam electrons with the Lorentz-factor $\gamma_b \sim 10^{8-9}$, giving the synchrotron emission in the $(0.01-400)$GeV energy domain.

According to Aliu et al. (2008) a joint fit to the EGRET (10MeV to 10GeV) and MAGIC (> 25GeV) data predicted a power-law spectrum with a generalized exponential shape for the cutoff, described as $F_\epsilon \propto \epsilon^{-\alpha}\exp(-(\epsilon/\epsilon_0)^\beta)$, where $\alpha = 2.022 \pm 0.014$. We provided a theoretical confirmation of the measured spectrum, which yielded $\beta = 1.6$ and the cutoff energy $\epsilon_0 = 23$GeV (Chkheidze et al. 2011). Recent VERITAS observations $(100-400)$GeV combined with the Fermi-LAT data $(0.1-10)$GeV favor a broken power law as a parametrization of the spectral shape. The good fit results are also obtained if one uses a log-parabola function, but it fails to describe the spectrum below 500MeV. Although, the Fermi-LAT and Magic data below 60 GeV can be equally well parameterized by broken power law and exponential cutoff. In the energy range between 100GeV and 400GeV measured by VERITAS and MAGIC, the spectrum is well described by a simple power law with the spectral index equal to 3.8 (Aliu et al. 2011; Aleksić et al. 2012).

The paper is organized as follows. In Sect. 2 we describe the emission model, in Sect. 3 we derive the theoretical synchrotron spectrum for the high and the very high energy γ-ray emission of the Crab pulsar and in Sect. 4 we discuss our results.

2 EMISSION MODEL

Any well known theory of pulsar emission suggests that, the observed radiation is generated due to processes taking place in the electron-positron plasma. It is generally assumed that the pulsar magnetosphere is filled by dense relativistic electron-positron plasma with an anisotropic one-dimensional distribution function (see Fig. 1 from Arons (1981)) and consists of the following components: a bulk of plasma with an average Lorentz-factor $\gamma \sim \gamma_p$, a tail on the distribution function with $\gamma \sim \gamma_t$, and the primary beam with $\gamma \sim \gamma_b$. The distribution function is one-dimensional and anisotropic and plasma becomes unstable, which might cause a wave excitation in the pulsar magnetosphere. The main mechanism of wave generation in plasmas of the pulsar magnetosphere is the cyclotron instability. The cyclotron resonance condition can be written as (Kazbegi et al. 1992):

$$\omega - k_{_\parallel} V_{_\parallel} - k_x u_x + \frac{\omega_B}{\gamma_r} = 0, \tag{1}$$

where $u_x = cV_{_\parallel}\gamma_r/\rho\omega_B$ is the drift velocity of the particles due to curvature of the field lines with the curvature radius ρ, $\omega_B \equiv eB/mc$ is the cyclotron frequency, e and m are the electron's charge and the rest mass, c is the speed of light, k_x is the wave vector's component along the drift and B is the magnetic field induction. During the wave generation process, one also has a simultaneous feedback of these waves on the resonant electrons (Vedenov et al. 1961). This mechanism is described by the quasi-linear diffusion (QLD), leading to a diffusion of particles as along as across the magnetic field lines. Therefore, resonant particles acquire transverse momenta (pitch angles) and, as a result, start to radiate through the synchrotron mechanism.

The wave excitation leads to redistribution process of the resonant particles via the QLD. The kinetic equation for the distribution function of the resonant electrons can be written as (Chkheidze et al. 2011):

$$\frac{\partial f^0}{\partial t} + \frac{\partial}{\partial p_\parallel}\{F_\parallel f^0\} + \frac{1}{p_\perp}\frac{\partial}{\partial p_\perp}\{p_\perp F_\perp f^0\} = \\ = \frac{1}{p_\perp}\frac{\partial}{\partial p_\perp}\left\{p_\perp D_{\perp,\perp}\frac{\partial f^0}{\partial p_\perp}\right\}. \tag{2}$$

where

$$F_\perp = -\alpha_s \frac{p_\perp}{p_\parallel}\left(1 + \frac{p_\perp^2}{m^2c^2}\right), \qquad F_\parallel = -\frac{\alpha_s}{m^2c^2}p_\perp^2, \tag{3}$$

are the transversal and longitudinal components of the synchrotron radiation reaction force, where $\alpha_s = 2e^2\omega_B^2/3c^2$ and $D_{\perp,\perp}$ is the transverse diffusion coefficient which is defined as follows (Chkheidze et al. 2011)

$$D_{\perp,\perp} = \frac{\pi e^4 n_p}{8mc\omega_B^2\gamma_p^3}|E_k|^2. \tag{4}$$

Here $|E_k|^2$ is the density of electric energy in the waves and its value can be estimated from the expression $|E_k|^2 \approx mc^2 n_b\gamma_b c/2\omega_c$, where ω_c is the frequency of the cyclotron waves. From Eq. (1) it follows that

$$\omega_c \approx \frac{\omega_B}{\delta\gamma_r}, \tag{5}$$

where $\delta = \omega_p^2/(4\omega_B^2\gamma_p^3)$, $\omega_p \equiv \sqrt{4\pi n_p e^2/m}$ is the plasma frequency and n_p is the plasma density.

The transversal QLD increases the pitch-angle, whereas force $F_\perp$ resists this process, leading to a stationary state $(\partial f/\partial t = 0)$. The pitch-angles acquired by resonant electrons during the process of the QLD satisfies $\psi = p_\perp/p_\parallel \ll 1$. Thus, one can assume that $\partial/\partial p_\perp >> \partial/\partial p_\parallel$. In this case the solution of Eq.(2) gives the distribution function of the resonant particles by their perpendicular momenta (Chkheidze et al. 2011)

$$f(p_\perp) = Cexp\left(\int \frac{F_\perp}{D_{\perp,\perp}}dp_\perp\right) = Ce^{-\left(\frac{p_\perp}{p_{\perp_0}}\right)^4}, \tag{6}$$

where

$$p_{\perp_0} \approx \frac{\pi^{1/2}}{B\gamma_p^2}\left(\frac{3m^9c^{11}\gamma_b^5}{32e^6P^3}\right)^{1/4}. \tag{7}$$

And for the mean value of the pitch angle we find $\psi_0 \approx p_{\perp_0}/p_\parallel \simeq 10^{-6}$. Synchrotron emission is generated as the result of appearance of pitch angles.

The synchrotron emission flux of the set of electrons in the framework of the present emission scenario is written as (see Chkheidze et al. (2011))

$$F_\epsilon \propto \int_{p_{\parallel min}}^{p_{\parallel max}} f_\parallel(p_\parallel) B\psi_0 \frac{\epsilon}{\epsilon_m}\left[\int_{\epsilon/\epsilon_m}^{\infty} K_{5/3}(z)dz\right] dp_\parallel. \quad (8)$$

Here $f_\parallel(p_\parallel)$ is the longitudinal distribution function of electrons, $\epsilon_m \approx 5\cdot 10^{-18} B\psi_0\gamma^2$GeV is the photon energy of the maximum of synchrotron spectrum of a single electron and $K_{5/3}(z)$ is the Macdonald function. After substituting the mean value of the pitch-angle in the above expression for ϵ_m, we get

$$\epsilon_m \simeq 5\cdot 10^{-18}\frac{\pi^{1/2}}{\gamma_p^2}\left(\frac{3m^5c^7\gamma_b^9}{4e^6P^3}\right)^{1/4}. \quad (9)$$

Accordingly, the beam electrons should have $\gamma_b \simeq (6\cdot 10^8 - 10^9)$ to radiate the photons in the energy domain $\sim (10-100)$GeV energy. The gap models provide the Lorentz factors up to 10^7, which is not enough to explain the detected pulsed emission. Consequently, the additional particle acceleration mechanism should be invoked to accelerate the fastest electrons to even higher energies.

According to Aliu et al. (2011) the observations of the Crab pulsar indicates that the HE pulsed emission should be produced far out in the magnetosphere. Therefore, we assume that the Langmuir waves (L) generated via the two-stream instability at the light cylinder length-scales undergo Landau damping on the fastest beam electrons, which results in their effective acceleration. Excitation of L waves through the two-stream instability in the relativistic electron-positron plasma is considered in a series of works (see e.g., Lominadze & Mikhailovskii (1979); Usov (1987); Asseo & Melikidze (1998); Ursov & Usov (1988); Gogoberidze et al. (2008)), where it is assumed that the instability develops due to overlapping of the fast and slow pair plasma particles at distances $r\sim 10^8$cm from the star surface. For typical parameters of pair plasma in the pulsar magnetospehers the growth rate of the instability is quite sufficient (see Gogoberidze et al. (2008)), that inevitably provides existence of L waves in the vicinity of the light cylinder zone. The phase velocity of the excited L waves is asymptotically close to the speed of light (Gogoberidze et al. 2008). Therefore, these waves can be only damped on the fastest electrons of the primary beam, which velocity equals the phase-velocity of the waves and the distribution function satisfies $\partial f_{b_0}/\partial p_\parallel < 0$. Taking into account the equipartition of energy among the plasma components $n_p\gamma_p = n_b\gamma_b/2$, one can estimate the energy density of L waves as the half of the energy density of the primary beam particles. Through the Landau damping process the energy of the waves is transferred to the small fraction of the beam electrons with the highest Lorentz factors. If we assign the density of these electrons as n^* and the Lorentz factors as γ^*, and equate the energy densities of particles and the L waves, we will get $2n^*/n_b \approx \gamma_b/\gamma^*$. The total density of the beam electrons is equal to the Goldreich-Julian density $n_b = B/Pce \approx 2\cdot 10^7 cm^{-3}$ (Goldreich & Julian 1969) and also if we take into account that $\gamma_b \sim 10^7$ and $\gamma^* \sim 10^9$, we find $n^* \sim 10^5 cm^{-3}$. As we see, if the wave energy is transferred to the fastest beam electrons, which number is two orders of magnitude smaller than the total number of the primary beam particles, they will gain the Lorentz factors up to 10^9. The observational fact, that the emission flux above 25GeV decreases should be caused by reduced number of emitting particles with the highest Lorentz factors.

It should be mentioned that during the Landau damping process the beam distribution function will be alongated and will form a high energy 'tail'on the distribution function. The final shape of the distribution function after the quasi-linear relaxation is the plateau, and the stationary state is reached. But in our case this might not be achieved as in the same region where the L waves are damped the cyclotron instability is developed, which involves the beam electrons into the cyclotron resonance process. This complicated process causing the redistribution of the resonant particles needs a more detailed investigation, which we plan to perform in our future work. In the present paper, we estimate the final shape of the distribution function which provides explanation of the measured spectrum.

The beam particles lose their energy through the synchrotron radiation, which sets the upper limit on the Lorentz factors that can be achieved during their acceleration process (de Jager et al. 1996). The maximum achievable value of γ can be estimated by equating the synchrotron radiative looses to the power of the emitting particles gained through the acceleration process, which in our case can be written as:

$$\frac{2}{3}\frac{e^4B^2\psi_0^2\gamma^2}{m^2c^3} = mc^2\gamma\Gamma_{LD}. \quad (10)$$

Here

$$\Gamma_{LD} = \frac{n_b\gamma_b\omega_b}{n_p\gamma_p^{5/2}}, \quad (11)$$

is the Landau damping rate, where $\omega_b = \sqrt{4\pi e^2 n_b/m}$ (Volokitin et al. 1987). The estimations show, that the Lorentz factor of the beam electrons that can be reached through the acceleration process $\gamma \lesssim 10^{19}$. Consequently, the limit on the energy of synchrotron photons in our case should be $\epsilon_{max}\sim 10^{54}$eV (see Eq. (9)), which inevitably allows generation of the observed ~ 100GeV photons from the Crab pulsar through the synchrotron emission mechanism.

3 SPECTRUM OF THE SYNCHROTRON RADIATION

To obtain the synchrotron emission spectrum in our case, we need to solve the integral (8). For this reason, first let us find the parallel distribution function of the beam electrons $f_\parallel$ during the QLD process of the cyclotron instability. By multiplying both sides of Eq. (2) on $p_\perp$, integrating it over $p_\perp$ and taking into account that the distribution function vanishes at the boundaries of integration, Eq. (2) reduces to

$$\frac{\partial f_\parallel}{\partial t} = \frac{\partial}{\partial p_\parallel}\left(\frac{\alpha_s}{m^2c^2\pi^{1/2}}p_{\perp 0}^2 f_\parallel\right). \quad (12)$$

For $\gamma\psi \ll 10^{10}$, a magnetic field inhomogeneity does not affect the process of wave excitation. The equation that describes the cyclotron noise level, in this case, has the form (Lominadze et al. 1983)

$$\frac{\partial |E_k|^2}{\partial t} = 2\Gamma_c|E_k|^2, \quad (13)$$

where

$$\Gamma_c = \frac{\pi^2 e^2}{k_{\parallel}} f_{\parallel}(p_{res}), \tag{14}$$

is the growth rate of the instability. Here $k_{\parallel}$ can be found from the resonance condition (1)

$$k_{\parallel_{res}} \approx \frac{\omega_B}{c\delta\gamma_{res}}. \tag{15}$$

Combining Eqs. (10) and (11) one finds

$$\frac{\partial}{\partial t}\left\{f_{\parallel} - \alpha\frac{\partial}{\partial p_{\parallel}}\left(\frac{|E_k|}{p_{\parallel}^{1/2}}\right)\right\} = 0, \tag{16}$$

$$\alpha = \left(\frac{4}{3}\frac{e^2}{\pi^5 c^5}\frac{\omega_B^6\gamma_p^3}{\omega_p^2}\right)^{1/4}. \tag{17}$$

Consequently, one can write

$$\left\{f_{\parallel} - \alpha\frac{\partial}{\partial p_{\parallel}}\left(\frac{|E_k|}{p_{\parallel}^{1/2}}\right)\right\} = const. \tag{18}$$

Taking into account that for the initial moment (the moment when the cyclotron instability arises) the energy density of cyclotron waves equals zero, the corresponding expression writes as

$$f_{\parallel} - \alpha\frac{\partial}{\partial p_{\parallel}}\left(\frac{|E_k|}{p_{\parallel}^{1/2}}\right) = f_{\parallel_0}. \tag{19}$$

Let us assume that $|E_k| \propto \gamma^{-m}$ (as there is no direct way to calculate the dependence $|E_k(\gamma)|$, we can only make an assumption and check its plausibility by fitting the theoretical emission spectrum with the observed one), in this case for the parallel distribution function we will have

$$f_{\parallel} \propto f_{\parallel_0} + \gamma^{-m-\frac{3}{2}}. \tag{20}$$

The initial distribution $f_{\parallel_0}$ of the beam particles in this case is the redistributed one after the Landau damping process. The final shape of the distribution function of resonant particles via the Landau damping when the stationary state is reached is the plateau. But in our case this might not be reached as in the same region develops the cyclotron instability. Thus we consider $f_{\parallel_0} \propto \gamma^{-n}$, where n is not close to zero. Consequently, the parallel distribution of the beam electrons is proportional to two power-law function with the indexes $m + 3/2$ and n.

The effective value of the pitch angle depends on $|E_k|^2$ as follows (Chkheidze et al. 2011)

$$\psi_0 = \frac{1}{2\omega_B}\left(\frac{3m^2c^3}{p_{\parallel}^3}\frac{\omega_p^2}{\gamma_p^3}|E_k|^2\right)^{1/4}. \tag{21}$$

Using expressions (8), (18) and (19), and replacing the integration variable $p_{\parallel}$ by $x = \epsilon/\epsilon_m$, we will get the synchrotron emission spectrum

$$F_{\epsilon} \propto \epsilon^{-\frac{2m+4n-1}{5-2m}}\left\{G_1\left(\frac{\epsilon}{\epsilon_m}\right)_{max} - G_1\left(\frac{\epsilon}{\epsilon_m}\right)_{min}\right\} + $$
$$+\epsilon^{-\frac{6m+5}{5-2m}}\left\{G_2\left(\frac{\epsilon}{\epsilon_m}\right)_{max} - G_2\left(\frac{\epsilon}{\epsilon_m}\right)_{min}\right\}, \tag{22}$$

where

$$G_1(y) = \int_y^{\infty} x^{\frac{2m+4n-1}{5-2m}}\left[\int_x^{\infty} K_{5/3}(z)dz\right]dx$$

$$G_2(y) = \int_y^{\infty} x^{\frac{6m+5}{5-2m}}\left[\int_x^{\infty} K_{5/3}(z)dz\right]dx. \tag{23}$$

The energy of the beam particles vary in a broad range $\gamma_b \sim 10^6 - 10^9$ in which case, we have $(\epsilon/\epsilon_m)_{max} \ll 1$ and $(\epsilon/\epsilon_m)_{min} \gg 1$. Under such conditions the functions $G_1(y) \approx G_2(y) \approx G(0)$. Consequently, we can assume that the synchrotron emission spectrum (Eq. (20)) is proportional to two power-law functions $\epsilon^{-\frac{2m+4n-1}{5-2m}}$ and $\epsilon^{-\frac{6m+5}{5-2m}}$. According to VERITAS observations the spectrum measured in the energy domain $(100-400)$GeV is well described by power-law with the spectral index equal to 3.8 (Aliu et al. 2011). When $m \approx 1$, we have $-(6m+5)/(5-2m) = -3.8$. At the same time, when $m = 1$ and $n = 1.2$, we find $-(2m+4n-1)/(5-2m) = -2$ that is in a good agreement with the observations in the 10MeV - 25GeV energy domain, which shows the power-law spectrum $F(\epsilon) \propto \epsilon^{-2.022\pm0.014}$ (Aliu et al. 2008).

4 DISCUSSION

The interesting observational feature of the Crab pulsar of the coincidence of pulse-phases from different frequency bands, ranging from radio to VHE gamma-rays (Manchester & Taylor 1980; Aliu et al. 2008, 2011) implies that generation of these waves occur in one location of the pulsar magnetosphere. This consideration automatically excludes the generally accepted HE emission mechanisms, the Inverse Compton (IC) scattering and the curvature radiation, which are not localized (Machabeli & Osmanov 2009, 2010). These particular issues have been considered by Machabeli & Osmanov (2010). Studying the curvature radiation it was found that the curvature drift instability is efficient enough to rectify the magnetic field lines (curvature tends to zero) in the region of the generation of high and the VHE emission, making the curvature emission process negligible. At the same time by analyzing the IC scattering, it was found that for Crab pulsar's magnetospheric parameters even very energetic electrons are unable to produce the observed HE photons.

In Lyutikov et al. (2011) it is argued that the main generation mechanism of the VHE emission of the Crab pulsar is the IC scattering of the soft UV photons by the secondary plasma particles. Particularly, it is assumed that the secondary plasma, which is produced due to cascades in the outer gaps of the magnetosphere is responsible for the soft UV emission via the synchrotron mechanism. This radiation plays the target field role for the IC scattering process. As a result, the VHE γ-ray emission is produced extending to hundreds of GeV. Let us consider the equation that gives the frequency of the photon after the IC scattering (e.g. Rybicki & Lightman (1979)):

$$\omega' = \omega\frac{(1-\beta\cos\theta)}{1-\beta\cos\theta' + (1-\cos\theta'')\hbar\omega/\gamma mc^2}, \tag{24}$$

where ω is the frequency before scattering, $\beta \equiv v/c$, $\theta = (\widehat{\mathbf{PK}})$, $\theta' = (\widehat{\mathbf{PK}}')$ and $\theta'' = (\widehat{\mathbf{KK}}')$ (by $\mathbf{P}$ we denoted the momentum of relativistic electrons before scattering, $\mathbf{K}$ and $\mathbf{K}'$ denotes the three momentum of photon before and after scattering, respectively). The emission maximum comes along the magnetic field lines. The pitch angles of the rela-

tivistic electrons moving along the magnetic field lines are very small ($\psi \sim 10^{-6}$ see Eq.(7)), accordingly as the UV emission is generated through the synchrotron regime, the angle θ should also be very small. Since we observe the well-localized pulses of the VHE emission, the angle $\theta' \ll 1$. Taking into account the observational fact of the phase coincidence of signals from different frequency bands, one should assume that $\theta \approx \theta'$. At the same time the coincidence of pulse signals of UV and the VHE emission gives $\theta'' = 0$. Consequently, the IC scattering of the soft UV photons by the secondary plasma electrons in case of the Crab pulsar should only cause the redistribution of the electrons, but can not provide the increase in the emission frequency, especially up to the VHE band. For significantly increasing the photon energy by the IC scattering processes without violating the condition of the pulse-phase coincidence, the angle θ must be large enough, which can not be provided by our model. Apparently, the IC scattering should play the main role in the generation of the high energy emission for pulsars with the large pulse profiles in soft energy domains.

The emission model proposed in the present paper implicitly explains the observed pulse-phase coincidence of low (radio) and high frequency (10MeV-400GeV) waves, as their generation is a simultaneous process and it takes place in the same place of the pulsar magnetosphere. In previous works (Machabeli & Osmanov 2010; Chkheidze et al. 2011) we applied this model to explain the HE (0.01-25GeV) pulsed emission of the Crab pulsar observed by the MAGIC Cherenkov Telescope (Aliu et al. 2008). It was found that on the light cylinder length-scales the cyclotron instability is arisen, which on the quasi-linear stage of the evolution causes re-creation of the pitch angles and as the result the synchrotron radiation mechanism is switched on. We assume that the source of the high and the VHE pulsed emission of the Crab pulsar is the synchrotron radiation of the ultrarelativistic primary beam electrons. To explain the observed high frequency gamma-rays by synchrotron mechanism the Lorentz factors of the emitting particles should be of the order of $10^8 - 10^9$ (see Eq. (9)). The highest Lorentz factor for the typical pulsar is $\sim 10^7$. Thus, we assume that such an effective particle acceleration is caused by existence of the Langmuir waves with the phase velocities $\upsilon_\varphi \lesssim c$ close to the velocities of the fastest beam electrons in the region close to the light cylinder. Consequently, the L (electrostatic) waves are efficiently damped on the most energetic primary beam electrons. The Landau damping causes the growth of a HE tail on the distribution function of the resonant electrons and inevitably throws the most energetic particles to higher Lorentz factors (up to $\gamma \sim 10^9$). At the same time the beam electrons acquire the pitch angles due to the cyclotron interaction with the transverse waves, which causes the synchrotron radiation processes giving the observed high and the VHE emission up to 400GeV. The distribution function tends to form the plateau (due to Landau damping), though the number of processes impede this. The reaction force of the synchrotron emission, scattering of L waves and the Compton scattering of photons on the beam particles also take place in process of formation of the distribution function of beam electrons. As the result, it is unlikely for the distribution to reach the shape of plateau and thus, we represent it as $f_{\|_0} \propto \gamma^{-n}$.

The calculation of the synchrotron emission spectrum by taking into account the processes described above (see Eq. (20)) and matching it with the observations shows that the emission spectrum in the 10MeV-25GeV energy domain depends on the power-law index n of distribution function of the beam particles. At the same time the emission spectrum in $(100-400)$GeV energy domain does not depend on n but only depends on m (see Eq. (18)). When $m = 1$ and $n = 1.2$ the emission spectrum well matches the measured one in both high $(0.01-25$GeV) and the very high $(100-400$GeV) energy domains. In previous paper (Chkheidze et al. 2011) explaining the HE (10MeV-25GeV) spectrum we obtained the power-law function with the exponential cutoff $F_\epsilon \propto \epsilon^{-2} exp[-(\epsilon/23)^{1.6}]$, as $\gamma_b \sim 10^8$ were the highest considered Lorentz factors of the emitting electrons. We assume that detection of the exponential cutoff at higher ($> 400GeV$) photon energies can not be excluded, the exact location of the cutoff energy is defined by the highest energy of the beam electrons that can be reached through the Landau damping before the particles reach the light cylinder. This particular problem needs more detailed investigation, which is the topic of our future work.

REFERENCES

Aleksić J. et al., 2011, ApJ, 744, 43

Aleksić J. et al., 2012, A&A, 540, 69

Aliu E. et al., 2008, Sci, 322, 1221A

Aliu E. et al., 2011, Sci., 334, 69

Arons J., 1981, in Proc. Varenna Summer School and Workhop on Plasma Astrophysics, ESA, 273

Asseo E., Melikidze G. I., 1998, MNRAS, 301, 59

Chkheidze, N., Machabeli, G., Osmanov, Z., 2011, ApJ, 730, 62

de Jager, O. C., Harding, A. K., Michelson, P. F., Nel, H. I., Nolan, P. L., Sreekumar, P., & Thompson, D. J. 1996, ApJ, 457, 253

Gogoberidze G., Machabeli G. Z., Usov V. V., 2008, PhRvE, 77, 7402

Goldreich, P., & Julian, W. H. 1969, ApJ, 157, 869

Kazbegi A.Z., Machabeli G.Z & Melikidze G.I., 1992, in Proc. IAU Collog. 128, The Magnetospheric Structure and Emission Mechanisms of Radio Pulsars, ed. T.H. Hankins, J.M. Rankin & J.A. Gil (Zielona Gora: Pedagogical Univ. Press), 232

Lominadze D. G., Mikhailovskii A. B., 1979, ZhETF, 76, 959

Lominadze J.G., Machabeli G. Z., & Usov V. V., 1983, Ap&SS, 90, 19L

Lyutikov et al., 2011, arXiv:1108.3824

Machabeli G.Z. & Usov V.V., 1979, AZhh Pis'ma, 5, 445

Machabeli G. & Osmanov Z., 2009, ApJ, 700, 114

Machabeli G. & Osmanov Z., 2010, ApJ, 709, 547

Manchester R.N. & Taylor J.H., 1980, Pulsars, F.H. Freeman and Company

Osmanov, Z., Shapakidze, D., & Machbeli, G., 2009, A&A, 509, 19

Rybicki G.B. & Lightman A. P., 1979, Radiative Processes in Astrophysics. Wiley, New York

Ursov V. N., Usov V. V., 1988, Ap&SS, 140, 325

Usov V. V., 1987, ApJ, 320, 333

Vedenov A.A., Velikhov E.P. & Sagdeev R.Z., 1961, Soviet Physics Uspekhi, Volume 4, Issue 2, 332

Volokitin, A.S., Krasnoselskikh, V.V. & Machabeli, G.Z., 1987, Soviet Journal of Plasma Physics, 11, 310